Sampling Strategies for Crop Yield Assessment Within and Among Crop Rotations

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ABSTRACT

Long-term two- and four-year crop rotations were designed to provide reliable information to formulate long-term strategies for crop sequencing that optimize crop and soil use options in the upper Midwest. Multilevel sampling and monitoring at the single plant, plants per unit area, and experimental plot levels were designed to quantify the spatio-temporal dynamics of corn, soybean and wheat crops in 192 geo-referenced main plots (MP), and their responses to alternative cropping systems, tillage, and fertility treatments. Baseline soil information and crop yield were collected from all 192 plots during 2002 and 2003. Data on plant grain area (G) per m^2, plant height (Ht), and midday differential canopy temperature (D) during the growing season, yield per plant and its components, and yield per m^2 at harvest, were collected in 2003 from two geo-referenced sampling sites (SP) within each of 16 plots per crop. The multivariate data set was analyzed with the objective of identifying the hierarchy of constraints to plant growth, development and yield, and to refine the sub-sampling strategy in future years. Averaged over crops, SP-based grain variance was 94.5% higher than the MP-based, however, SPs were more efficient than MPs in detecting crop-specific significant yield differences due to management factors. Conventional system, conventional tillage and N fertilizer resulted in highest grain yield, whereas organic system, strip tillage and no N fertilizer resulted in lowest grain yields. Yield-limiting factors were crop-specific, with strip tillage and no N fertilizer highly limiting corn yield, and organic system and no N fertilizer being the most limiting factors in soybean and wheat. G, Ht and D loaded highly on two components explaining >80.0% of variability in grain yield. However, relative importance of G and Ht in explaining yield variability decreased, and that of D increased with successive samplings during the growing season.

Keywords: Crop rotations, sub-sampling, multivariate analysis

INTRODUCTION

Researchers and farmers, particularly in the upper Midwest, realized that research is needed to identify cropping systems that simultaneously improve the economic and social viability of farmers and rural communities while protecting the environment and improving or maintaining the natural resource base (Johnson et al., 2003). It is postulated that systems which increase crop diversity, reduce tillage and reduce the use of external inputs potentially will improve economic, social and environmental sustainability (Smolik and Dobbs, 1991). Long-term experiments are needed to determine yield trends, estimate nutrient dynamics and balances, understand changes in yield, predict soil carrying capacity and assess system sustainability (Regmi et al., 2002).

Plants, as individual organisms and as populations, are critical factors in determining the productivity of agricultural systems, in general, and crop rotations, in particular (Tokalidis, 2001). A large number of constraints may limit the productivity and production of crop plants within a particular crop rotation. These include crop species, soil, weather and management factors and their interactions (Porter et al., 2003). Crop growth and production may respond differently to these factors depending on the varietal differences in architecture, yield characteristics and response to biotic and abiotic stresses (Tokalidis, 2001).

Detailed measurements on sub-samples of single plants and plant populations are needed to quantify the spatial and temporal dynamics in crop rotations and cropping systems, adjust biological and grain yields when measured in large plots, and provide reliable information to formulate long-term strategies for crop sequencing that optimize crop and soil use options. The objectives of this study were to (1) determine which management factors and plant attributes affect crop yield estimates based on main- and sub-plot sampling, and (2) identify the hierarchy of constraints to plant growth, development and yield of corn, soybean and wheat in a cropping sequence context.

MATERIALS AND METHODS

Two crop rotations (two-yr, corn-soybean and four-yr, corn-soybean-wheat-alfalfa-alfalfa), were established in 2002 on 192 geo-referenced plots (6 x 12 m each) in a randomized complete block design at the Swan Lake Research Farm near Morris, MN. The experiment included four replicates of all phases of each crop rotation. Organic and conventional systems (Sy) and strip tillage (Tl) with or without the recommended nitrogen fertilizer rates (Fr) for each crop were randomized within each replicate. Apparent electrical conductivity (EC_a) was measured in all 192 plots prior to planting and 42 soil physical, chemical and biological variables were measured in soil samples from each of the 192 main plots. Two geo-referenced sub-sampling plots (1 m^2 each) representing factor combinations in the experiment were established in each of 64 main plots. Yield data were collected in 2002 and 2003 from all plots and were based on a 15 m^2 harvested area. In 2003 data were collected seven to nine times from the sub-sampling plots between Julian dates 122 and 223 on foliage development as percent green area (G) of surface area until 100% soil cover was reached, plant height (Ht), number of plants/unit area (NP), and at harvest, number of seed (NS) and seed weight (SW)/unit area. The midday differential canopy temperature (D) readings taken at key phenological stages in the 64 sub-sampling plots and at physiological maturity on all 192 main plots were calculated. Factor analysis was used to group soil variables into factors based on the correlation matrix of the variables (Hair et al., 1998).

Partial Least Square (PLS) Regression was used to identify a linear combination of the explanatory variables (i.e., management factors, in addition to

G, Ht and D) that gives latent vectors that optimally predict the response variable (i.e, yield) (Joernsgaard and Halmoe, 2003). The number of PLS factors to be retained was determined by a cross-validation procedure (StatSoft, 2002). Temporal variation (patterns) of G, Ht and D were statistically analyzed by calculating the ratio of variance/mean of each plant attribute. If this ratio=1.0, <1.0, or >1.0, then the distribution of these variables over time is random, more uniform than random, or contagious (over-dispersed), respectively. Deviations of these ratios from unity were tested by a *t* test (Zar, 1996). The AMMI1 (statistical model of additive main effect and multiple interactions) biplot (Ma et al., 2004) was used to visualize the crop x management practice two-way data. This biplot allows visualization of the main effects of the crops (corn, soybean and wheat) and the treatments (eight combinations of two levels each of systems, tillage and N fertilizer) in addition to the crop x management interactions.

Yield data (main-plot data in 2002 and 2003 and sub-plot data in 2003) were standardized (Zar, 1996) before analysis (i.e., mean=0.0 and variance=1.0) and single degree of freedom contrasts were used for mean comparisons among main factor levels and among the two-way and three-way interaction levels. For each crop (corn, soybean, wheat and alfalfa), crop rotation (two- and four-year) and cropping system (organic and conventional), the hierarchy of constraints to plant growth, development and yield were identified based on main- and sub-plot yield and plant attribute data. This information was used to characterize cropping systems as to their productive capacity. Statistical analyses were performed using STATISTICA (StatSoft Inc., 2001) unless otherwise specified.

RESULTS

Grain Yield

Mean yield estimates based on two sub-samplings (1 m^2 each) for corn, soybean and wheat were 8.35 ± 1.9, 2.52 ± 0.48 and 3.73 ± 1.02 $Mgha^{-1}$, respectively. The respective values based on main plots averaged over two years (2002 and 2003) (15 m^2) were 8.5 ± 1.3, 2.0 ± 0.27 and 4.03 ± 1.02 Mg ha^{-1}. However, all yield estimates deviated from normal distribution (Shapiro-Wilk (SW-W) test statistic >0.87, p<0.05).

Frequency distribution of percent grain yield deviation from the overall mean for main- and sub-plots (Fig. 1) indicated that both are normally distributed (SW-W=0.981, p=0.31 and 0.984, p=0.44, respectively); the two distributions are significantly correlated (r=0.72, p<0.002). However, slightly lower correlation coefficients were found for soybean (r=0.57, p=0.00) and wheat (r=0.61, p=0.00) as compared to corn (r=0.80, p=0.00). However, the actual and predicted frequency of ~0.0 deviations from the mean is higher in the sub-plots as compared to the main-plots.

Sub-plot harvested area was 13.3% of main plot area; however, the variance associated with yield estimates from sub-plots was on average 94.5% higher than the variance estimated on main-plot basis. The ratios between variance values associated with grain yield of corn, soybean and wheat based on main and sub-plot sampled areas were 0.51, 2.7 and 0.65, respectively; however the ratio between main and sub-plot areas was 7.5.

Soil Analysis

The first three factors derived through factor analysis explained 72.0% of total variation in the original 42 variables and were retained for further statistical analysis. Soil inorganic carbon (C), soil pH and available P have high loadings of the first factor, F1. The soil in the experimental plots tends to be calcareous, consistent with pH between 7 and 8 and high levels of inorganic C, primarily in the form of calcium carbonate. The availability of P is pH dependent. At pH 7.5 and above, phosphorus (P) interacts with calcium reducing available P. These factors appeared, singly or in combination, in four of the six PLS regression models.

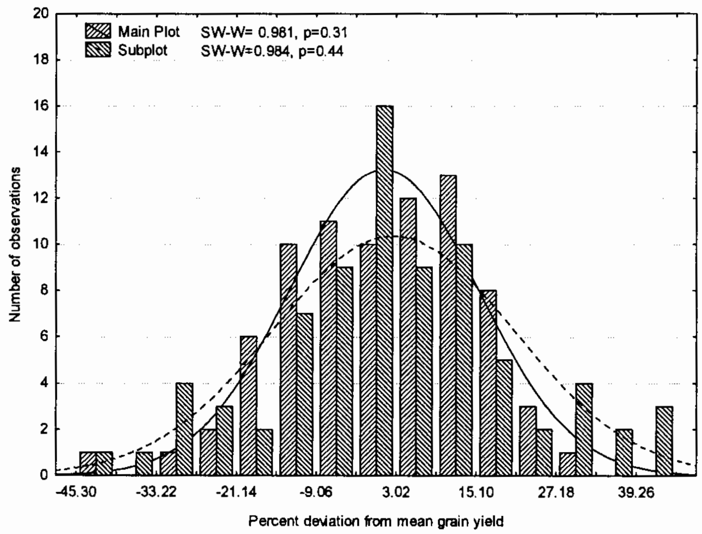


Figure 1. Frequency distribution of percent deviations from the overall grain mean yield for corn, soybean and wheat in two- and four-year crop rotation in main- and sub-plots.

Microbial biomass, percent sand and percent K have high loadings on F2, suggesting that sand content is more important in characterizing the soil than clay or silt content alone. Both microbial biomass C and percent K were negatively correlated with percent sand ($r=-0.23$, $p=0.05$ and $r=-0.47$, $p=0.05$, respectively); this implies reduced exchange sites for K as a result of decreased clay and organic matter content. The relationship between sand and microbial biomass may be indirect via an expected reduction of soil organic matter as sand increases.

Total N, total C, nitrate N and bulk density have high loadings on F3. The amount of nitrate N that is available is a function of microbial mineralization, which utilizes C and N sources. Bulk density reflects porosity; nitrification is an aerobic process, and high bulk density increases the likelihood of anaerobic conditions or anaerobic micro sites thus reducing nitrification.

Fractal analysis of the first three factors derived from the soil analysis data indicated that the fractal dimension and its standard error ($D_0 \pm$ s.e.) for the first (F1), second (F2) and third (F3) factors were 1.888±0.428, 1.798±0.302, and

1.853±0.444, respectively. The respective R^2 values were: 0.709, 0.816 and 0.685. Exponential models in the isotropic semivariogram analysis fit the data adequately and resulted in R^2 values of 0.75, 0.84 and 0.79 for F1, F2 and F3, respectively.

Grain Yield Deviation from the Mean

Percent deviation from overall mean grain yield in the main and sub-plots due to main factors and their two- and three-way interactions are presented in Table 1. All deviations from the mean were normally distributed, except in main plot corn (SW-W=0.897, p=0.01). Significant differences, based on single degree of freedom contrasts, were found among levels of all three main factors in five of the 18 possible contrasts (28%). Higher numbers of pair-wise significant differences were detected among levels of the two-way (18 of 36 or 50%) and the three-way (14 of 24 or 58%) interactions. Moreover, most (64%) of the pair-wise significant differences in the three-way interactions were detected in the sub-plots. Variance estimates in sub-plots of corn and wheat were 60 and 52% higher and in soybean 63% lower than the variance in their respective main plots.

Grain yield of corn, soybean and wheat, whether measured on main- or sub-plot basis, were negatively impacted by organic system, strip tillage and no fertilizer-N application. The largest and statistically significant percent deviation between conventional and organic systems was found in the main and sub-plot yield of corn. A similar, albeit not significant, trend was observed for soybean and wheat. Strip tillage significantly reduced corn yield as compared to conventional tillage, whereas wheat yield was negatively and significantly impacted by the lack of N fertilizer.

Two- and three way interactions among levels of main factors impacted grain yield of all crops in a predictable manner. The highest negative percent deviations in grain yield were associated with organic system, strip tillage and no N fertilizer. Crops differed markedly in their responses to the two-way interactions of these factors, with highest positive (33.9%) and negative (-37.7%) yield deviations observed for corn yield associated with conventional system-N fertilizer and organic system-strip tillage combinations, respectively. The impact of three-way interaction on crop yield was more pronounced than the main factors or their two-way interactions. A positive (41.5%) and highly significant yield deviation from the mean was observed for the conventional system-conventional tillage-N fertilizer combination, whereas the lowest was observed for the organic system-strip tillage-no N fertilizer combination.

Results from the PLS analysis showed that the percent variation (Average R^2 of Y) in main- and sub-plot grain yield explained by the first four components (Table 2) differed among crops. The R^2 values and R^2 increments for the respective number of components are relative to the sums of squared deviations from the origin (0.0) for the centered predictor variables (X) and dependent (response, i.e., main- and sub-plot yield) variables (Y).

Four components (Table 2) accounted for a minimum of 86.0 to a maximum of 96.0% of the variability in grain yield. The corresponding R^2 values for the predictor variables ranged from 49.0 to 62.0%. Individual R^2 values for main and sub-plot yield estimates varied among crops and among main- and sub-plots within each crop. R^2 increments for the first two components were significant for all three crops, whereas the R^2 increments for the remaining two components were relatively small (1.0 to 8.0%) and non-significant. Additionally, these two components were chosen on the basis of their low amount of residual variation in the response variable (data not presented). Therefore, only the first two components were retained for further statistical analyses.

Table 1. Percent deviation from grain mean yield in main- and sub-plots of corn, soybean and wheat and results of single degree of freedom contrasts due to main management factors and their interaction in two- and four-year crop rotations.

System	Tillage	Fertilizer	Corn		Soybean		Wheat	
			Main	Sub	Main	Sub	Main	Sub
C†			0.211a	0.294a	0.095	0.092	0.052	0.030
O			-0.21b	-0.29b	-0.096	-0.087	-0.053	-0.027
	C		0.106b	0.333a	0.067	0.021	0.007	-0.033
	S		-0.11a	-0.33b	-0.069	-0.022	-0.008	0.036
		Y	0.064	0.063	0.023	0.032	0.099	0.123a
		N	-0.065	-0.064	-0.025	-0.041	-0.100	-0.12b
C	C		0.259b	0.406a	0.134	-0.008	0.101	0.057
C	S		0.164a	0.185b	0.059	0.025	0.002	0.012
O	C		-0.05b	0.262	0.003a	0.049	-0.086	-0.099
O	S		-0.38a	0.168	-0.20b	-0.068	-0.109	0.066
C		Y	0.244	0.339a	0.149a	0.154a	0.136a	0.135a
C		N	0.179	0.151b	0.044b	-0.037b	-0.03b	-0.05b
O		Y	-0.12a	-0.37b	-0.101	-0.028	0.062a	0.114a
O		N	-0.31b	-0.22a	-0.093	0.010	-0.15b	-0.22b
	C	Y	0.183a	0.453a	0.115a	0.027	0.138a	0.054
	C	N	0.029b	0.113b	0.021b	-0.069	-0.13b	-0.093
	S	Y	-0.054	-0.287	-0.067	-0.037	0.059	0.174a
	S	N	-0.159	-0.285	-0.070	-0.005	-0.071	-0.15b
C	C	Y	0.295	0.415a	0.190	0.123a	0.209a	0.168a
C	C	N	0.222	0.295b	0.096	-0.108b	-0.01b	0.00b
C	S	Y	0.193	0.282a	0.105	0.051	0.063	0.117a
C	S	N	0.134	0.107b	0.011	-0.001	-0.058	-0.09b
O	C	Y	0.071a	0.290a	0.094	0.053	0.068a	-0.01a
O	C	N	-0.16b	0.132b	-0.033	0.030	-0.24b	-0.20b
O	S	Y	-0.20a	-0.21a	-0.11a	-0.125	0.056	0.231a
O	S	N	-0.45b	-0.41b	-0.25b	-0.02	-0.093	-0.26b
Shapiro-Wilk test			0.897	0.935	0.987	0.964	0.982	0.987
p-value			0.01	0.06	0.92	0.59	0.90	0.88
Variance			0.048	0.077	0.0118	0.00437	0.0107	0.0163

†, System C=conventional, O=organic, Tillage C=conventional, S=strip, N fertilizer Y=yes, N=no.

Factor loadings on the first two components are presented in Figs. 2a and b for main- and sub-plots of corn, respectively. The first and second components combined accounted for 0.88 and 0.92 of yield variability in main- and sub-plots of corn, respectively. The first component, by far, was the most important and had high loadings in decreasing order in the main plots of: system>Ht2>Ht1>G1>D1>F1>D2. The remaining factors, except tillage, had low loadings on component 1 which accounted for 0.67 of total variation in grain yield of main plots, whereas component 2 accounted for a much smaller (0.21) portion of the variation. Factor loadings on component 1 for sub-plots of corn followed a similar trend, with the following decreasing order: system>Ht2>Ht1>G1>D3> Tillage>D1. The first and second components explained 0.73 and 0.19 of total variation in grain yield of sub-plots of corn, respectively.

Table 2. First four partial least squares (PLS) regression components and R^2 of response (yield, Y) and predictor (X) variables in main- and sub-plots of corn, soybean and wheat in two- and four-year crop rotations.

Crop	Sampling unit (Y)	Component	Increase R^2 of Y	Average R^2 of Y	Increase R^2 of X	Average R^2 of X
Corn	Main plot	1	0.67**	0.67	0.29	0.29
		2	0.21*	0.88	0.15	0.44
		3	0.04	0.92	0.08	0.51
		4	0.02	0.94	0.05	0.56
	Subplot	1	0.73**	0.73	0.28	0.28
		2	0.19*	0.92	0.17	0.45
		3	0.04	0.96	0.12	0.57
		4	0.006	0.96	0.05	0.62
Soybean	Main plot	1	0.70**	0.70	0.21	0.21
		2	0.11*	0.81	0.10	0.31
		3	0.03	0.84	0.10	0.41
		4	0.02	0.86	0.08	0.49
	Subplot	1	0.63**	0.63	0.26	0.26
		2	0.13*	0.76	0.14	0.40
		3	0.08	0.84	0.06	0.46
		4	0.03	0.87	0.09	0.55
Wheat	Main plot	1	0.70**	0.70	0.22	0.22
		2	0.20*	0.90	0.08	0.30
		3	0.05	0.85	0.07	0.37
		4	0.01	0.96	0.11	0.48
	Subplot	1	0.79**	0.79	0.22	0.22
		2	0.10*	0.89	0.11	0.33
		3	0.04	0.93	0.14	0.47
		4	0.02	0.95	0.10	0.57

A different set of factors contributed to the first two components accounting for 0.81 and 0.76 of total variation in grain yield of main- and sub-plots of soybean, respectively. The first and second components accounted for 0.70 and 0.11 of total variation in grain yield of soybean in main plots. Factors having high loadings on component 1 were of the following decreasing order in main-plots: G2>G1>D3>System> D2>Ht2 >Ht1>Tillage >N fertilizer; the two- and three-way interactions of management factors had relatively smaller loadings on this component. The first and second components accounted for 0.63 and 0.13 of total variation in grain yield of soybean in sub-plots, factors with high loadings on the first component, in decreasing order, were: Ht3> Ht2> Ht1> System x tillage>G1>N fertilizer>F1>System x Tillage x N fertilizer. System and tillage had lower loadings than their interaction on component 1 in sub-plots.

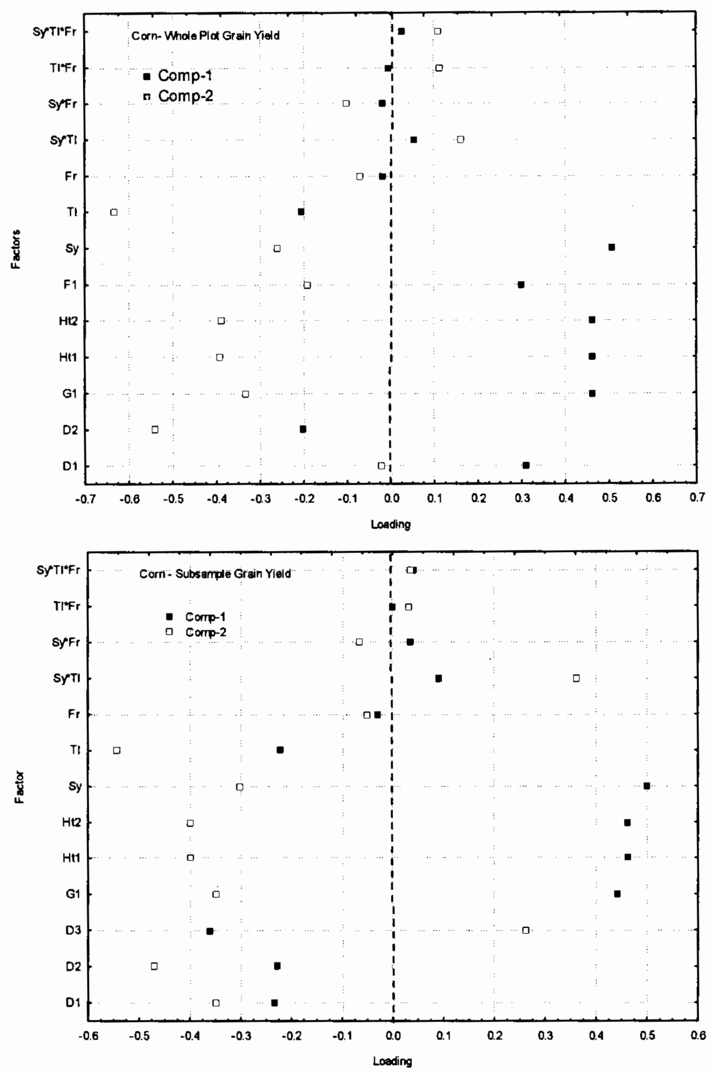


Figure 2a, b. Factor loadings on the first two PLS components for corn in main- (a) and sub-plots (b).

Almost equal proportions of variability in wheat grain yield in main- (0.90) and sub-plots (0.89) were accounted for by the first 2 components. However, different factors loaded differently on the first component which accounted for 0.70 and 0.79 of total variation in grain yield in main- and sub-plots, respectively.

The following factors were associated with component 1 in main-plots, in decreasing order: D2>G2>G1>N fertilizer>F2>F1>D3>Tillage>System x tillage

>System. The ranking of factors on component 1 in sub-plots, in decreasing order was: G1>D1>D2>N fertilizer>F3>D3> System x Tillage >Tillage x N fertilizer>System x N fertilizer >system.

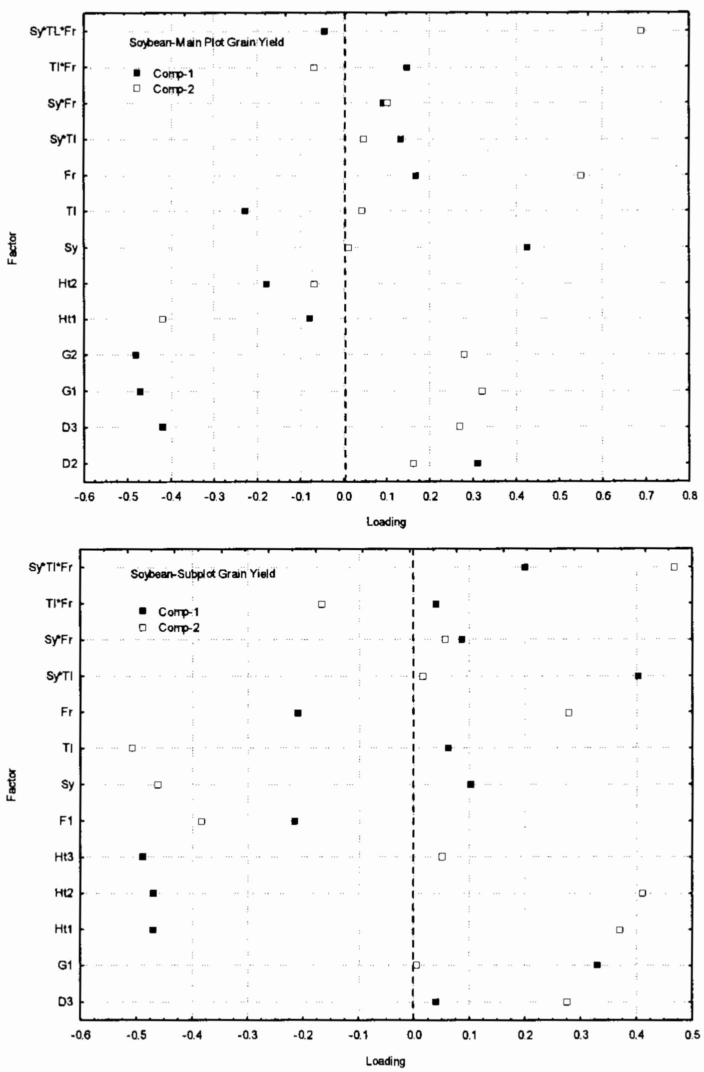


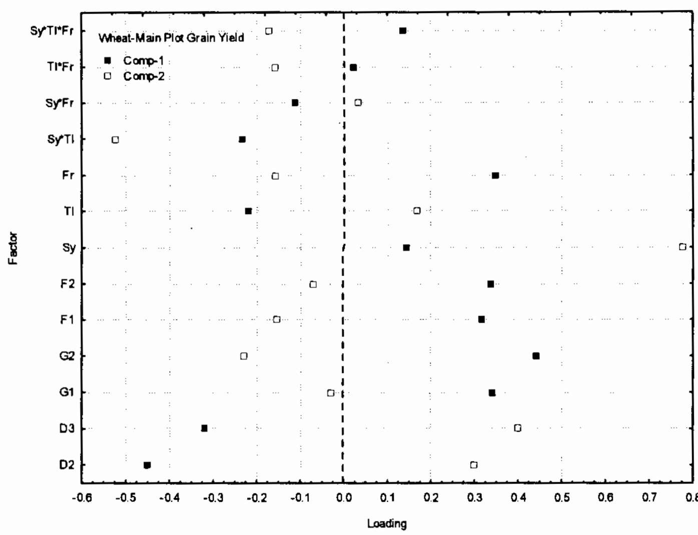
Fig 3a, b. Factor loadings on the first two PLS components for soybean in main- (a) and sub-plots (b).

Plant Attributes

Plant canopy cover (G), plant height (Ht) and midday differential canopy temperature (D) for corn, soybean and wheat differed in their loadings on the first two components and they were more influential in explaining a larger portion of yield variability than the management practices. They appeared in the first two components of main- and sub-plot at different frequencies, with D1<D2=D3, G1>G2>G3 and Ht1=Ht2>Ht3, however, D's loadings on the first component increased, whereas loadings of G and Ht decreased with time (in

Julian days). On the other hand, F3 had higher loading on component 1 than F1 and F2 combined.

Loadings of D, G and Ht on Corn's first component followed a similar trend in main- and sub-plots. They ranked for main-plots in the following manner: Ht2=Ht1=G1>D2>D1; the respective ranks for sub-plots were Ht2>Ht1>G1 >D3>D2>D1. A different pattern was observed for the same variables' loadings on the first component in main- and sub-plots of soybean and wheat. The ranking in main-plots for soybean was G2>G1>D3>D2>Ht2>Ht1 and in the sub-plots Ht3>Ht2>Ht1>G1>D3. Finally the ranking in main plots of wheat was D1>G2>G1>D3, and in wheat sub-plots was: G1>D1>D2>D3.



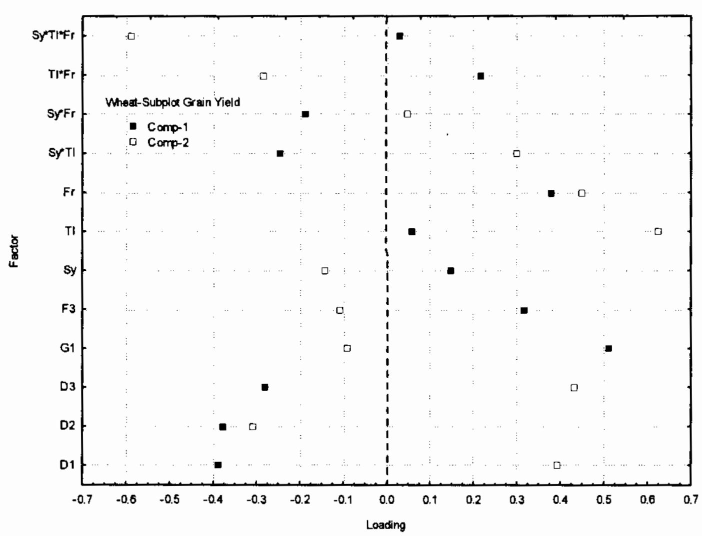


Fig 4a, b. Factor loadings on the first two PLS components for wheat in main- (a) and sub-plots (b).

Those predictors with small loadings are less important than those with large loadings in absolute value. The loadings plots show a few X-variables that are weighted at nearly zero, especially for component 1. These variables add little to the model fit and removing them may improve the model's predictive capability. Examples of these factors are N fertilizer (Fr), system x N fertilizer (Sy*Fr), tillage x N fertilizer (Tl*Fr) and system x tillage x N fertilizer (Sy*Tl*Fr) in Fig. 2a, and tillage x N fertilizer (Tl*Fr) in Fig. 1b and Fig. 4a.

ANOVA and Variance Component Analysis

Three plant attributes (G, Ht and D) (Table 3) responded differently to main management factors and their interactions. On average, tillage explained the highest (31.91%) variation in these attributes across crops, whereas the system x tillage x N fertilizer interaction component explained the least (1.41%).

Frequency of significant "percent variance in G, Ht and D" due to main management factors and their interaction was below average (28 out of 63, or 44.0%); however, respective values for main factors and their interactions were 70 and 25%. System had the highest value (78.0%), followed by tillage and N fertilizer (67.0% each). The factor "system" explained a highly significant portion of variation in Ht of wheat (68.43%), whereas the factors including the two- and three-way interactions of management factors explained the least, however; there were a few exceptions (e.g., system x fertilizer for D-corn and D-soybean).

Average cumulative variance explained by management factors ranged from 65.3% for plant canopy cover to 54.4% for plant height; the respective value for midday differential canopy temperature was intermediate (60.0%). Percent variance in plant canopy cover, plant height and midday differential canopy temperature explained by three management factors and their interactions indicated that tillage, system and N fertilizer, in decreasing order influenced these three variables in corn, soybean and wheat in different manners. These three management factors and their two- and three-way interactions accounted for 61.0% of total variance in the plant attributes; the highest in G-wheat (70.0%), and the lowest in Ht-wheat (42.5%).

ANOVA results for all three plant attributes and for each crop are summarized as percent significant differences among treatment means. Relatively small (18.3) to medium (43.3) percent significant differences among all possible 120 pair-wise mean comparisons (n=16) were significant. Treatment combinations, with the highest and lowest percent deviation from the mean, are presented in Table 3. Conventional system and N fertilizer, irrespective of tillage level (i.e., conventional or strip), contributed to higher deviations from the mean, whereas organic system and strip tillage contributed to lower deviations from the mean across crops and plant attributes.

The highest percent deviation from the mean (42.1) was found for plant height in wheat and it was due to the combined effect of conventional system, strip tillage and N fertilizer. However, the highest deviation (26.5) below the mean was found for plant canopy cover in soybean in response to conventional system, strip tillage and no N fertilizer.

Temporal variance (expressed as the ratio between variance and mean values for each plant attribute and crop) ranged from a high of 2.44 for plant canopy cover in corn to 0.49 for plant height in soybean. These values indirectly

Table 3: Percent variance in plant canopy cover, plant height and midday differential canopy temperature explained by three factors and their two-way and three-way interactions in corn, soybean and wheat in two- and four-year crop rotations.

Factors		Plant Canopy Cover (G)‡			Plant Height (Ht)			Midday Differential Canopy Temperature (D)		
		Corn	Soybean	Wheat	Corn	Soybean	Wheat	Corn	Soybean	Wheat
	Mean	Variance component (% of total variance explained by factors)								
System	24.72a†	21.25*	46.54*	68.43*	54.38*	27.58*	45.29*	19.45*	8.76	5.81
Tillage	31.91a	16.64*	6.96	1.13	16.62*	18.06*	13.54*	9.46	29.56*	42.21*
Fertilizer	7.68b	17.29*	15.14*	21.32*	4.29	4.73	14.57*	23.75*	7.87	22.61*
System x Tillage	22.09a	14.14*	9.50	1.69	23.06*	36.62*	15.27*	4.02	4.15	4.48
System x Fertilizer	8.49b	26.11*	2.46	1.93	0.32	4.15	1.53	41.05*	47.22*	7.58
Tillage x Fertilizer	3.26b	4.34	11.22	19.45*	1.06	7.00	7.54	0.97	1.71	2.40
System x Tillage x Fertilizer	1.41b	0.21	3.31	9.46	0.25	1.81	2.24	1.25	0.73	14.9*
Cumulative variance, %		62.0	64.0	70.0	59.3	61.4	42.5	60.7	59.0	60.5
% Sig. Diff. among treatment means, N=16		18.3	25.0	43.3	18.3	25.0	18.3	30.8	31.25	31.25
Temporal variance		2.44a§	2.10a	0.86b	0.83a	0.49b	0.32b	1.15	1.06	1.00
Treatment with highest value (% above the mean)		CCY 14.0*	OSY 21.8*	CSY 42.1**	CCY 31.0**	OCY 28.9**	CSY 22.5*	CSY 25.7*	CCY 36.6**	CSY 27.4**
Treatment with lowest value (% below the mean)		OSY 13.8*	CSN 26.5**	OSN 10.3	OSY 13.5*	CSN 17.0*	OSN 10.8	OSY 20.5*	OSY 19.4*	OSN 16.7*

†, Means followed by the same letter do not differ significantly p<0.05; *, **, Significant at the 0.05 and 0.01 level of probability, respectively.

§, Means, within each trait, followed by the same letter do not differ significantly, p<0.05.

‡, Average of three readings each taken on Julian dates: G: 170 (G1), 212 (G2), 223 (G3). Ht: 181 (Ht1), 206 (Ht2), 223 (Ht3). D: 188 (D1), 212 (D2), 251 (D3)

reflect the diverse responses of plant attributes in all three crops to management (and environmental) variables. Temporal variation in G (wheat), Ht (corn) and D (corn, soybean and wheat) did not differ significantly from one (i.e., random); however, G (corn and soybean) was over-dispersed and Ht (soybean and wheat) were more uniform than random.

The partial correlation coefficients between temporal variance and each of percent deviation from the mean of the highest and lowest treatment combinations ($r=-0.86$, $p=0.01$ and $r=0.45$, $p=0.05$, respectively) suggest that management factors contributing to lower temporal variance in all three plant attributes enhance the development of higher plant canopy cover, and taller plants with higher midday differential canopy temperature (i.e., actively transpiring plants).

Treatment combinations with significantly higher and lower value expressed as % of the mean were dominated by CSY (67.0%) and OSY (44.4%), respectively. The remaining treatments with values significantly higher than the mean were OCY, OSY and CCY; whereas, the remaining treatment combinations with values significantly lower than the mean were OSN (33.3%) and CSN (22.2%). Crop-specific treatments resulting in significantly highest (CSY) and lowest (OSN) values were found for corn and wheat, but not for soybean.

AMMI Analysis

Mean standardized yield for each treatment combination is presented in Fig 5. IPCA1 accounted for 98.3% of the crop x management interaction sum of squares and separated the organic from conventional systems. CCY followed by CCN had the highest standardized yields (1.07 and 0.97, respectively) averaged over crops; whereas, OSN (-1.78) and OSY (-0.98) had the lowest. Corn yield was associated with, and showed positive deviation from mean grain yield (main- and sub-plots) on four treatment combinations in the order: CCY>CCN>CSY>CSN. Soybean yield was negatively impacted by organic system regardless of tillage and N fertilizer treatment levels. Although CCY had a positive impact on soybean yield, other treatment combinations negatively impacted its yield in the following order: OSN>OSY>OCN. Wheat yield was associated with and responded favorably to CCY>OSY; however, OCN, in particular impacted yield highly negatively

DISCUSSION

In this long-term study, we will be able to quantify the effects of treatment combinations applied to a fixed rotation and, at the same time, compare the effects of different rotations on the performance of crops under similar management practices (Yates, 1954). In fixed-rotation experiments, the interest lies in the cumulative effects not over years *per se* but over entire cycles of rotations. Therefore, each phase in a rotation appears each year as an important feature in the design of long-term rotational experiments (Singh et al., 1997).

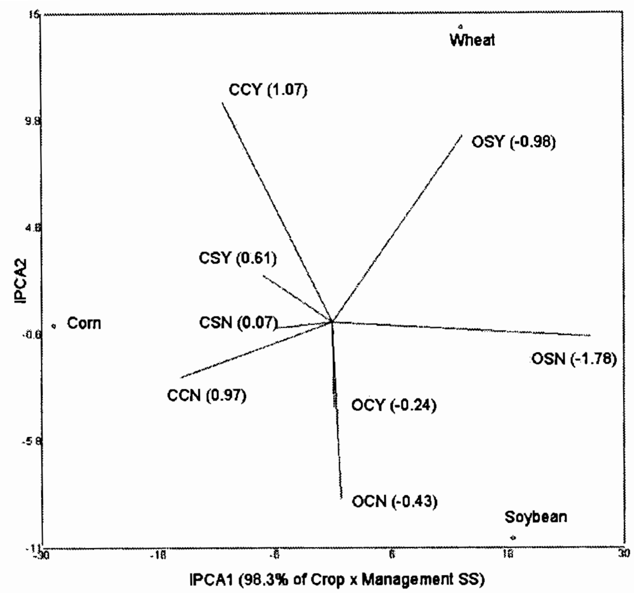


Fig 5. Biplot of the first two principal components of management factor combinations (system, tillage and N fertilizer) and their interaction with crops (corn, soybean and wheat averaged over grain yield of main- and sub-plots) in two- and four-year crop rotations (see Table 2, for abbreviations).

Porter et al. (2003) documented how rotation length and management strategies influenced productivity after the initial four establishment years of crop rotations. However, we utilized extensive data sets collected during the initial years of this long-term experiment to monitor soil and crop variables and their interaction with management and weather variables. A thorough multivariate statistical analysis of soil chemical, physical and biological properties, climatic data, plant attributes and crop yields is useful for understanding relationships among site variables and between these variables and crop yields at a scale that couldn't be achieved without data collected during the initial years of this long-term experiment (Mallarino et al., 1999).

Results of this study indicated that the PLS method was effective in reducing information existing in a large data set. It effectively detected explanatory variables associated with factors that explained large portion of crop x management factors interaction. In this data set, several yield components and plant attributes were highly correlated; however, Vargas et al. (2001) noted that the PLS method deals appropriately with this problem. Furthermore, the cross-validation procedure was a useful tool in determining the optimal number of significant components (factors) required for explaining crop x management interaction. Vargas et al. (2001) proposed PLS regression method as a more direct and parsimonious linear model to overcome the problems of multicollinearity and retaining the optimal number of principal components derived from environmental and other variables associated with AMMI models and factorial regression.

The AMMI1 biplot was constructed by plotting the main effects of crops and treatment combinations against their respective interaction scores, which are symmetrically scaled scores of the first-interaction principal component (IPCA1) resulting from subjecting the double-centered interaction matrix to singular-value decomposition (Ma et al., 2004). A crop x management interaction was found to be dominant factor in the biplot, 98.3% of which was explained by the first IPCA (Fig 5).

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